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THE UNIVERSITY OF ALBERTA

# MAGNETIZATION OF $UPt_3$

by

Ado Umezawa

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

EDMONTON, ALBERTA

FALL 1986

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.....

Supervisor

.....

.....

.....

Date 17 Sept. 1986

## DEDICATION

To my parents, who've put up with me for so long.

## ABSTRACT

$UPt_3$ is an unique material among rare earth and actinide systems for not only is it a heavy fermion superconductor ($\gamma \sim 420$ mJ/mol $K^2$, $T_c \sim .5$ K), but the existence of a $T^3 \ln T$ term in the specific heat seems to suggest it as being a spin fluctuator as well. This interplay between spin fluctuation and superconductivity in turn suggests a possibility of the superconductivity being of something other than the usual B.C.S. singlet pair. The confirmation of such speculation would make $UPt_3$ the first non-singlet superconductor to be discovered.

Flux-gate magnetometry is found to be quite favorable for measuring the magnetization of $UPt_3$ due to its sensitivity and relative ease in construction and measurement. Its sensitivity range being in the range of $10^{-3}$ to 10 Oe makes it ideal for measuring the magnetization of $UPt_3$ as well as many other rare earth and actinide systems. The core of this thesis will cover the building and testing of the flux-gate magnetometer and its magnetization measurements on $UPt_3$.

## ACKNOWLEDGEMENT

As with any project, this one owes very much to very many whose guidance and assistance made this "journey" not only possible but also very enjoyable. Firstly, I am in great debt to my advisor, Dr. K. Kadowaki, whose presence and guidance made impossible tasks possible and difficult ones easy. With the many skills obtained from him, the "paths" ahead have become much easier to travel.

I would also like to thank the members of Dr. S.B. Woods' research staff; Dr. N. Ali, Mr. W. Miner, Mr. M. Mohamed and Mr. T. Valian for their helpful advice and criticism. I am grateful towards my examining committee Dr. F. Khanna, Dr. J.S. Rogers and Dr. M.L. Waynman for their time and trouble taken for the expert review and criticism of my work. I would also like to thank Dr. H. Matsumoto of the University of Alberta, Dr. Y. Onuki of The University of Tsukuba, Drs. G.W. Crabtree, L. Hall, Mr. W.K. Kwok and Miss M. Vrtis of Argonne National Laboratory for their friendly and very helpful advice towards my work. I also owe so much to Mrs. P. Anderson, whose typing of my manuscript and patience toward my mistakes prevented me from losing my sanity during my frustrating attempt to complete my thesis.

Throughout my life and various "journeys", I have been fortunate to have the company of many people who are very close to me. They have advised me on which "paths" I should take or avoid. They have helped me out of wrong

"paths" that I have sometimes taken. Finally they have helped me overcome the obstacles often encountered on these "paths". These people are my parents, Hiroomi and Tamae Umezawa, as well as Rui and Linda Umezawa, Mrs. Tatsue Yamagami and Miss Yukako Akiyama.

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## 1. Introduction

Lanthanide and actinide rare-earth systems have been subject to much recent investigation, particularly at low temperatures. These materials exhibit several behaviors which are often described in terms of f-orbital interactions, extending from the local moment state to itinerant systems, and their characteristics may be classified with respect to the changing nature of these f-band electrons.

For a normal metal, like copper, measurements of the specific heat, C at low temperatures fit the expression

$$C = \gamma T + \beta T^3 \qquad (1\text{-}1)$$

where $\gamma$ is the electronic specific heat co-efficient, and $\beta$ is the lattice or phonon specific heat co-efficient. Thus when C/T is plotted as a function of $T^2$, a straight line is obtained with intercept $\gamma$ on the C/T axis at T=0 and slope $\beta$. Among the rare earth materials some exist which, after a temperature region in which C/T is relatively normal, exhibit a dramatically increasing specific heat below ~10K which finally results in an intercept value that is many times larger than the one that would have occurred had the specific heat C/T behaved linearly with respect to $T^2$ for very low temperatures. This very large low temperature specific heat is attributed to the electrons and it is noted that for a free electron model $\gamma$ is proportional to the effective mass $m^*$ of the conduction electrons. Thus these materials with large $\gamma$ are appropriately classified as heavy fermion

systems, and some display an effective mass as large as three orders of magnitude greater than the normal free electron mass.

Furthermore, many of these systems, in addition to their high $\gamma$ values exhibit other unexpected characteristics. One of these is superconductivity which has been discovered in the three compounds $CeCu_2Si_2$, $UBe_{13}$ and $UPt_3$, so far. The high $\gamma$ value is most likely due to a strong interaction of the f-orbital electron with neighboring electrons of non-f character, possibly to the point of forming a hybridized band (D.D. Koelling et al. 1985). If this is the case, then, although these systems may still undergo a phase ordering, superconducting transition, their behavior cannot be treated with the general B.C.S. Hamiltonian, but must include the many-body effects from the f-non f interaction and the f-f repulsion.

Of the three heavy fermion superconductors, there seems to be a possibility that $UPt_3$ is a non-singlet state superconductor. This is still just speculation with arguments on both sides of the singlet-triplet controversy. Since there are so few heavy fermion systems known, and since no accepted theory has been published yet, it is difficult to go beyond speculation. Still, the possibility of a non-singlet ground state proves to be attractive and increases the interest in any experimental measurement of this material.

One such measurement is magnetization, which, like the specific heat, depends on the electronic mass. Thus, by measuring the magnetization of $UPt_3$, one can obtain another measure of the effective mass. Magnetization becomes a particularly useful tool in the analysis of heavy fermion systems because of the large magnetic moments that these ions involve. There are several methods for measuring magnetization, one of which is using a flux-gate magnetometer. The advantage of flux-gate magnetometry over other methods is the simplicity in construction and use combined with a relatively high measurement sensitivity. This method is particularly useful in doing magnetization measurements in heavy fermion and other rare earth research because, unlike the ac methods that are often used, the zero of magnetization always gives zero output.

## 2. Heavy Fermion Systems

In 1979 Steglich, Aarts, Bredl Lieke, Meschede, Franz and Schäfer discovered bulk superconductivity in the system $CeCu_2Si_2$ (Steglich et al. 1979). When the specific heat measurements were done, they observed that the C/T values were not linear with respect to $T^2$. Beginning at about 14K they took a dramatic upswing and increased until they reached an intercept of 1100 mJ/mole $K^2$. Other heavy fermion systems also exhibit similar results.

If we assume that these systems follow the specific heat function (1-1), it is possible that this delinearization is produced by a change in either the intercept $\gamma$ or the slope $\beta$. The $\beta$ term is derived from the phonon properties of the metal while the $\gamma$ term arises from the electron properties. If the $\beta$ value was the affected variable resulting in the delinearization, then to accommodate such a change, the slope $\beta$ would have to go from a positive value to an extremely large negative value. Such a change in $\beta$ would accompany a significant change in the lattice vibrations, such as could be brought about by a structural change or phase transition. Since no such changes have been observed in these heavy fermion systems, it is very unlikely that the $\beta$ value is the main cause of the rise in the specific heat. Thus the alternative is that it results from $\gamma$. Furthermore, when the superconducting discontinuity in the specific heat

was observed by Steglich et al. at 0.5 K, its size helped confirm that the electronic specific heat must be very large. It should be noted that $UBe_{13}$ and $UPt_3$ also exhibit high superconducting specific heat discontinuities (Ott et al. 1983, Stewart et al. 1984). As stated earlier, the $\gamma$ value represents the electronic heat capacity contribution of the free electron Fermi gas. This can be written in the form

(2-1) $C_{el} = 1/3\ \pi^2 D(\varepsilon_F) k_B^2\ T \equiv \gamma T$

where the density of states is given by:

(2-2) $D(\varepsilon) = (V/2\pi^2)(2m^*/\hbar^2)^{3/2}\varepsilon^{1/2}$.

At the Fermi energy level (2-2) can be rewritten

(2-3) $D(\varepsilon_F) = (V/2\pi^2)(2m^*/\hbar^2)^{3/2}\varepsilon_F^{1/2}$

where the Fermi energy is given as

(2-4) $\varepsilon_F = \hbar^2/2m^*\ (3\pi^2 N/V)^{2/3}$

or

(2-5) $\varepsilon_F^{1/2} = \hbar/(2m^*)^{1/2}(3\pi^2 N/V)^{1/3}$.

Using (2-5) and (2-3), the specific heat contribution of the free electron Fermi gas can be written:

(2-6) $C_{el} = (\pi V/3)^{2/3} N^{1/3} k_B^2 m^*/\hbar^2 T$

from which

(2-7) $\gamma = (\pi V/3)^{2/3} N^{1/3} k_B^2 m^*/\hbar^2$.

Thus, if we assume that the number of electrons per unit volume, N/V, changes very little with respect to temperature, then $\gamma$ is proportional to $m^*$. In fact it is not uncommon to

express the ratio of thermal effective mass $m^*$ and the electron mass m as a ratio of the observed to the free electron $\gamma$ value.

(2-8) $m^*/m \equiv \gamma_{observed}/\gamma_{free}$

To understand the meaning of $\gamma_{free}$, one may use the fact that for a free electron gas $D(\varepsilon_F)$ can also be written

(2-9) $D(\varepsilon_F) = 3N/2\varepsilon_F$.

Then (2-1) becomes

(2-10) $\gamma = (\pi^2/2)N\, k_B^2(1/\varepsilon_F)$,

where N/V can be written in terms of the density of states at the Fermi surface.

(2-11) $N/V = (2g/3\hbar^2)N(0)\varepsilon_F$

so $\gamma$ can be written in terms of N(0), the density of states at the Fermi surface:

(2-12) $\gamma = (\pi^2 g/3\hbar)N(0)k_B^2 V$

When the units of N(0) are states/eV atom then

(2.13) $\gamma = nN(0)/0.4244$ [mJ/k$^2$mol]

where n is the number of atoms contributing conduction electrons in each unit cell. Thus it is the value obtained from (2.13) that is compared in (2.8) to the experimentally observed $\gamma$ and gives a mass ratio which, in the case of heavy fermion systems, is very large indeed.

In general, a $\gamma$ value greater than 400 mJ/(f atom mol K$^2$) has been considered to define a heavy fermion material (Stewart 1984), although systems with lower $\gamma$ values have

also been called heavy. Very recent de Haas-van Alphen measurements in $CeCu_6$ at a temperature of 20 mK, where the electrons are certainly in the high mass state, reveal cyclotron masses up to 40 m, but, as expected, the signal amplitude was very small for specimens of the best available quality at present. Further unpublished results were reported at the International Conference on Anomalous Rare Earths and Actinides held at Grenoble, France in July, 1986 from dHvA data on $UPt_3$. Fairly complete Fermi surface information yielded effective masses from 30 m to 90 m, certainly the highest cyclotron masses seen to date.

A discussion similar to that based on specific heat can be based on the paramagnetic susceptibility of the conduction "electrons" in heavy fermion substances. The Pauli spin magnetization of the conduction electrons for the paramagnetic state is given by the equation

(2-14) $M = \mu^2 D(\varepsilon_F) H$

where $D(\varepsilon_F)$ is the density of states at the Fermi level given in equation (2-3). It may be rewritten using (2-5)

(2-15) $D(\varepsilon_\varphi) = (V/\pi^2)^{2/3}(3N)^{1/3}(m^*/\hbar^2)$.

Now, the magnetization and the magnetic field intensity can be related in terms of the magnetic susceptibility

(2-16) $M = \chi H$.

From (2-14) and (2-15) it can be seen that the paramagnetic susceptibility is directly related to the effective mass of

the conduction electrons.

(2-17) $\chi \propto m^*$.

Thus the paramagnetic susceptibility of heavy fermion systems should be many orders of magnitude larger than normal metals, and by calculating the paramagnetic susceptibility of these systems, a value for the electronic effective mass may be obtained. In reality however, the actual value of $m^*$ is difficult to calculate from the experimentally observed $\chi$ since it is difficult to know the amount of susceptibility which is contributed by paramagnetism of the electrons. Nevertheless, a rough observation of the effective mass can be obtained by observing the magnetic susceptibility of the system, particularly when $m^*$ is very large.
Also by observing $\chi$ and M in these systems, some information about their magnetic characteristics can be obtained.

To get a basic understanding of these heavy fermion systems, the existing localized f-electrons bound to the rare earth and actinide groups must be taken into consideration. In the case of most rare earth systems, the 4f electrons must be considered while for the actinides, it is the 5f electrons. It is thought that these electrons are affected by two types of interactions which contribute to the heavy fermion behavior. Firstly; there is the interaction which exists among the f-electrons, often called the f-f interaction. This Coulomb repulsion interaction can be represented by the energy term

(2-20) $U \propto e^2/|r_1-r_2|$

So with a small $|r_1-r_2|$, the energy U becomes large. For a single f-f interaction, the simple solution to reduce U would be to maximize $|r_1-r_2|$. However, in these materials where several f-f interactions are taking place, the many body effects tend to arrange these electrons at the proper sites to minimize the energy U. This produces a localization of the f-electrons at these sites.

There is also the interaction between the f-electrons and the s, p and/or d electrons which tend to hybridize with the f electrons. In terms of band theory, this would be characterized by an overlap of the localized f electrons with the conduction band (Crabtree, 1986).

To give a simple example in terms of electron densities, consider an electron band below the Fermi energy which is completely localized at one energy state. This would appear as a thin line on the electron density spectrum. With a large Coulomb repulsion however, occupancy of the same site becomes difficult, making this line spread out to accommodate all the electrons which must go to different energy states. However, once these states are occupied, the same Coulomb repulsion will tend to keep these electrons from moving to other sites, thus preventing further broadening of the peak. Furthermore, the many body effects of the interaction will tend to renormalize the states closer to the

Fermi energy where, in the case of heavy fermion systems, it overlaps slightly with the Fermi level. This overlap produces a hydbridization effect between the f band and the conduction electrons. The term that is said to describe this interaction is often called the "Kondo resonance". This hybridization, at low temperatures, is then thought to produce a sharp peak at the Fermi energy where the new charge carriers, which still conduct, now find it harder to move due to the high localization characteristics of the f electrons. Thus, phenomenologically speaking, "heavy" in these systems means the difficulty with which these hybridized carriers can move. A list of the existing heavy fermion systems has been included in Table 2-1.

**Table 2-1**

| Compound | $\gamma$(mJ/mol K) | Ordering* | S-S spacing(A) | Reference |
|---|---|---|---|---|
| $CeCu_2Si_2$ | 1100 | S | 4.1 | Steglich et al (1979) |
| $UBe_{13}$ | 1100 | S | 5.13 | Ott et al (1983) |
| $UPt_3$ | 450 | S | 4.1 | Stewert et al (1984) |
| $NpBe_{13}$ | 900 | M | 5.13 | Stewert et al (1984) |
| $U_2Zn_{17}$ | 535 | M | 4.39 | Ott et al (1984) |
| $UCd_{11}$ | 840 | M | 6.56 | Fisk et al (1984) |
| $CeAl_3$ | 1600 | None | 4.43 | Andres et al (1975) |
| $CeCu_6$ | 1600 | None | 4.83 | Stewert et al (1984) |

*- S = superconductivity
M = magnetism

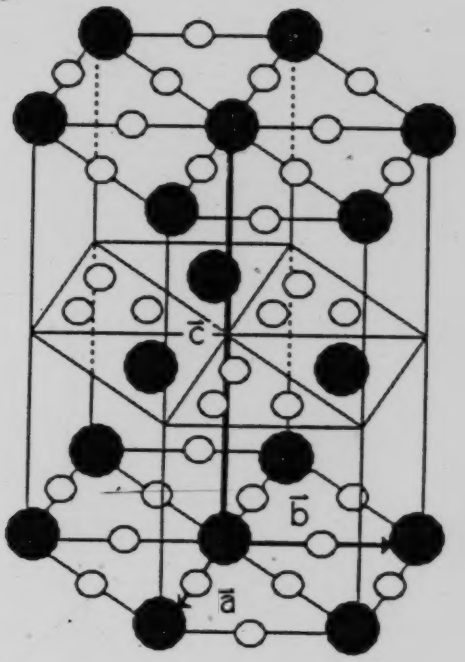
3. $UPt_3$

$UPt_3$ is a hexagonal D019 group compound of $MgCd_3$ structure with a distance between uranium atoms of 4.1 Å. (Pearson, 1958, Sticht and Kübler, 1985). (fig. 3-1) The unit cell contains 6 uranium atoms and 18 platinum atoms. The transverse axis has a length of 5.764 Å in the unit cell while the longitudinal axis has a length of 4.899 Å. The compound has a density of 19.4 $g/cm^3$ and a molar mass of 823.3 g/mol.

The specific heat measurements on $UPt_3$ were first done by Frings, Franse, de Boer and Menovsky (1983). The plot of C/T vs $T^2$ for $UPt_3$ revealed an upswing in C/T at approximately 10 K as the temperature was lowered, which resulted in an intercept $\gamma$ = 420 mJ/mol $K^2$ at T = 0K, making it the third heavy fermion superconductor discovered, following $CeCu_2Si_2$ and $UBe_{13}$. Its superconducting transition temperature, $T_c$, was measured by Stewart Fisk, Willis, and Smith (1984) to be at 0.54 K. Unlike $CeCu_2Si_2$ and $UBe_{13}$ however, the temperature dependence of the specific heat seemed to include, in addition to the $\gamma T$ and $\beta T^3$ terms, a $\delta T^3 \ell nT$ term. This term suggested the presence of spin fluctuations in $UPt_3$ (Brinkman and Engelsberg, 1968, Doniach and Engelsberg, 1966) because of its similarity to the $T^3 \ell nT$ term of the nuclear spin fluctuations in superfluid $^3He$ (Greywall, 1983).

fig. 3-1

$UPt_3$




$MgCd_3$ type D019 structure of $UPt_3$
Note: c-axis has been enlarged for viewing ease.

If this turns out to be true, these spin fluctuations could be precursors to a non-singlet superconducting state whose energy excitations may be the magnons. This analysis was further enhanced when Chen, Lambert, Maple, Fisk, Smith, Stewart and Willis (1984) observed a $T^2$ term in the resistivity just above $T_c$. Their data could be represented by

(3-1) $R = R_o + AT^2$

Of course a $T^2$ dependence in resistivity by itself is not sufficient to demonstrate that spin fluctuations exist in $UPt_3$, however it confirms the electronic specific heat results. The spin fluctuations have a pair breaking effect on the usual BCS superconducting Cooper pairs (singlet states). Thus it has been speculated that superconductivity in $UPt_3$ is of the triplet state. The confirmation of such a statement would make $UPt_3$ the first non-singlet superconductor to be discovered. In this light, it can be understood that $UPt_3$ is undergoing much investigation.

Magnetoresistance measurements done by Kadowaki et al. (1986) and de Visser et al. (1986) showed a positive slope with respect to magnetic field. This positive magnetoresistance is in contrast with that of other heavy fermion systems but is characteristic of antiferromagnetic spin fluctuating system. Antiferromagnetic spin fluctuations will be enhanced by an applied field with a peak occurring in

the resistivity at some critical field (Usami, 1978). This peak was observed in $UPt_3$ by de Visser et al. at 12T.

Josephson tunneling (Poppe, 1985) has been attempted on $UPt_3$ to determine the existence of spin fluctuations and the results, although they initially appeared positive were in general inconclusive. However ultrasonic attenuation observed by Bishop has produced results uncharacteristic of singlet superconductors thus pointing to higher order pairing. Furthermore thermal expansion measurements of $UPt_3$ done by de Visser et al. (1985) revealed pronounced spin-fluctuation contributions at low temperatures.

Finally the alloying of $UPt_3$ with palladium has been done by Stewart, Giorgi (1985) and by de Visser et al. (1986a) to yield interesting results. The superconductivity in $UPt_3$ becomes depressed with a 1.0% alloying of Pd while 20% alloying of Pd results in the total suppression of both the spin fluctuations and the upturn in the specific heat (large $\gamma$ value). This seems to indicate that the heavy fermion state as well as its superconductivity depends heavily on the hybridization of the f-electrons in uranium with the non-f electrons on their neighboring sites.

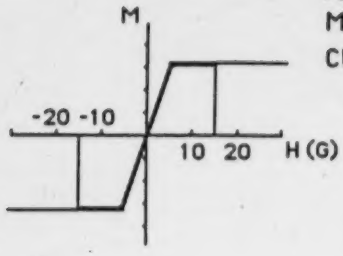
## 4. Magnetization

There are several methods for measuring the magnetic properties of solid state materials, one class of which involves measuring the magnetic force on a specimen in an inhomogeneous magnetic field. Because it is difficult to suspend a specimen freely so that the force on it can be measured at temperatures below ~ 2 K, other methods have been devised particularly for the low temperature region. Nuclear magnetic resonance (nmr) techniques may be used when the nuclear component of the magnetization is of interest and recently superconducting quantum interference devices (SQUID) have been used as very sensitive detectors of magnetization changes. Although both methods are useful, they are rather complex and difficult to build or use. Because of the complexity of these systems they are often built for very specialized purposes, such as low temperature thermometry, that are hard to modify for different purposes. An alternate method for measuring susceptibility and magnetization was used by Andres and Wernick (1973) for nuclear magnetic thermometry with $AuIn_2$. This method may not have quite the high sensitivity of the SQUID system, but where the magnetic measurements involve rare earth or more specifically heavy fermion systems, whose magnetic spin susceptibility is quite strong, its simplicity in use and lower sensitivity to external electromagnetic disturbances make this method a highly suitable one for measurements below ~ 10 K.

The magnetometer used was designed around a Hewlett-Packard 428B clip-on d.c. milliammeter with a 3529 A field probe attachment. The sensor of the probe, which is operated as a flux-gate, is very sensitive to changes of the magnetic flux density, B, in which it is located. The field sensor within the attachment consists of a pair of ferrite cores, each having its own counterwound excitation coil. This system is then enclosed by a third coil used as both a secondary and a feedback coil. The ferrite cores have a symmetric magnetization cycle with a low saturation point. (fig. 4-1) An AC field that will drive the cores to saturation is produced within the milliammeter. The two excitation coils are wound in opposing sense so that the magnetization they produce is 180° out of phase. The inductance of these driving coils and the signals transformed to the secondary are primarily due to the ferrite cores and once saturation occurs, the signal induced in the secondary coil becomes insignificant (i.e. $d\phi/dt \to 0$). Thus the inductive signals occur in the unsaturated regions only and the "peaks" will be antisymmetric when there is no externally applied field. (fig. 4-2a for core 1 and 4-2b for core 2). Thus when there is no externally applied field, the sum of the two core signals will be zero (fig. 4-2c).

However, in a non-zero external field, the ferrite cores no longer drive through a symmetric magnetization cycle (fig. 4-3). The result is that the signals from the two

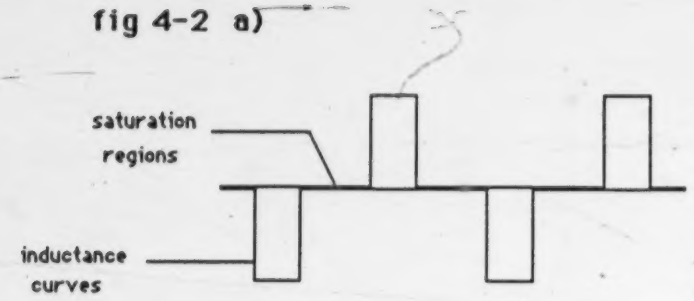
fig 4-1




FERRITE CORE MAGNETIZATION CURVE

$H_{ext}=0$

fig 4-2 a)




FERRITE CORE INDUCTANCE SIGNALS

fig 4-2 b)

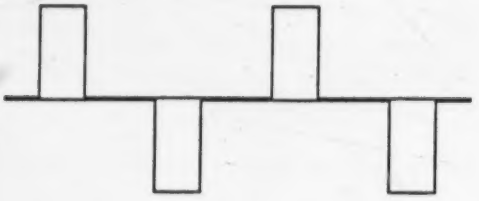
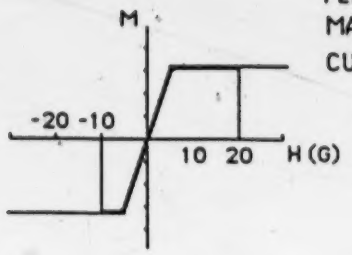


fig 4-2 c)

NET INDUCTANCE CURVE

fig 4-3




FERRITE CORE MAGNETIZATION CURVE

$H_{ext} \neq 0$

fig 4-4 a)

FERRITE CORE INDUCTANCE SIGNALS

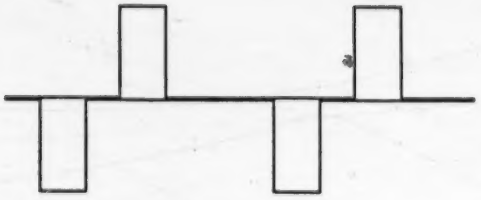


fig 4-4 b)

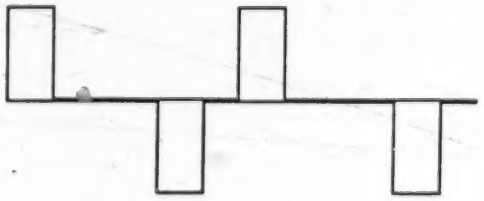
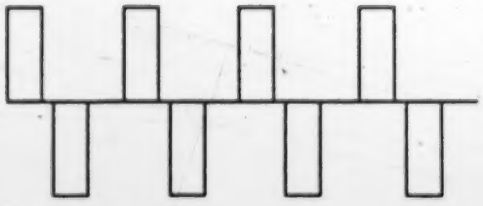


fig 4-4 c)

NET INDUCTANCE CURVE



ferrite cores are not exactly antisymmetric and thus their sum does not cancel. In such a case, the sensor generates a (negative) current in the feedback coil which holds the field at the cores very nearly zero. In the 428B milliammeter a resistor is placed in this feedback circuit to produce an output voltage proportional to the applied field. This field sensor when used in conjunction with a flux transformer made up the flux-gate magnetometer used to measure $UPt_3$ and other rare earth materials.

The basic operation of the superconducting flux transformer is that of a magnetic transformer within which the total magnetic potential must be constant,

(4-1) $\phi_T$ = constant,

The total flux consists of the flux through the probe, $\phi_p$, through the connecting wires $\phi_t$, and the (astatic) specimen coil, $\phi_c$ (fig. 4-5)

(4-2) $$\phi_T = \phi_p + \phi_t + \phi_c$$
$$= i_t(L_p + L_t + L_c).$$

In order to make the gain of the system as large as possible $L_t$ must be made negligible.

(4-3) $\phi_t \ll \phi_c, \phi_p$

or

(4-4) $L_t \ll L_c, L_p$.

This is done by twisting the connecting wires to avoid any uncompensated loops in the wire. With $L_t$ minimized to insignificance, (4-2) becomes

(4-5) $\phi_{tot} = i_t(L_p + L_c) = \text{constant}$

From (4-5) it can be observed that since the total flux of the system is constant and the inductance of the coil at the probe $L_p$ is constant, then any change in $L_c$, which will occur if the magnetization of its core changes, will result in a change in $i_t$. Thus a change in the magnetization of the sample will produce a transformer current, $\Delta i_t$, whose field, $\Delta B$, at the probe ($\vec{A}$; fig 4-5) will register on the milliammeter. Therefore, if we know the relationship between the magnetic field changes at the specimen coil and the current registered on the milliammeter, this instrument can be used to measure the field produced by the sample within the flux-gate magnetometer.

To illustrate the sensitivity of the flux-gate magnetometer, a very simple example can be taken. The general expression for the field strength of an infinite solenoid is given by the expression

(4-6) $H = ni\ 4\pi$

in Gaussian units, where n is the number of turns per unit length of the coil and i is its current. Consider the field sensor sensitivity to be $\Delta H_{min}$ where

(4-7) $\Delta H_{min} = 10^{-4}$ Gauss

then from (4-6), the corresponding current that will travel along the transformer circuit is

(4-8) $\Delta i_{min} = \Delta H_{min}/4\pi n$

fig 4-5

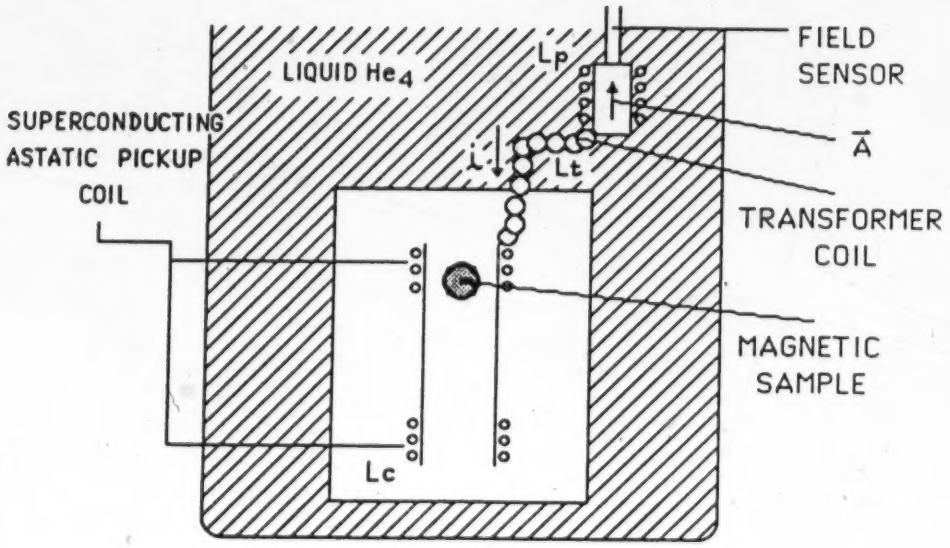



fig 4-6

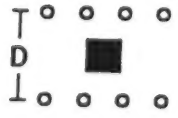
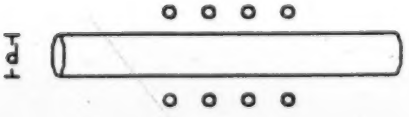



fig 4-7



Choosing some arbitrary n which will keep $\Delta i_{min}$ small while leaving the response efficiency high, (i.e. n=20) then the current corresponding to $\Delta H_{min}$ is:

(4-9) $\Delta i_{min} = 10^{-4}/80\pi \sim 4\times10^{-8}$ Amperes

or 40 nanoamps. From this simple estimate one can observe the magnitude of the signal efficiency of the fluxgate and thus get an idea of the possible sensitivity of the magnetometer.

In the case of magnetization measurements, the relationship between magnetization and the magnetic field intensity is given by the susceptibility $\chi$.

(2-18) $M = \chi H$

For a coil, the magnetic flux $\phi$ can be written in terms of the magnetization by the equation:

(4-10) $\phi = 4\pi MF$

where F is the filling factor of the sample within the coil. For example for the case where the space within the coil is a vacuum and no sample is present within the coil then the filling factor is simply unity.

(4-11) $F = 1$

However, if a sample was to be placed within the coil, the the uniformity of the field would be affected, thus requiring an appropriate revision in the filling factor.

(4-12) $F < 1$

The particular form of this revision is determined by the

shape of both the sample and the coil. To determine F, two cases may be considered. The first case is that in which the sample length is shorter than the coil, such that the sample fits completely within the coil. For such a case, the filling factor can be calculated from the equation

(4-13) $F = V/D$

where V is the volume of the sample and D is the diameter of the coil (fig. 4-6). The alternate case occurs when the sample is longer than the coil. In this case since the entire length of the coil is filled with the sample, the filling factor is only concerned with the sample's cross sectional area. For example, for a cylindrical piece of sample whose length is longer than the coil (fig 4-7), the filling factor would be written as:

(4-14) $F = \pi d^2/4$

where d is the diameter of the sample. For the latter case, since there is no field distortion from the ends, once the sample is symmetrically within the coil, it is often the preferred case. The flux-gate magnetometer reads the actual flux passing through its specimen coil. So from a knowledge of the volume or cross sectional area of the sample and using equation (4-10), the change in the flux can be used to find

fig 4-8

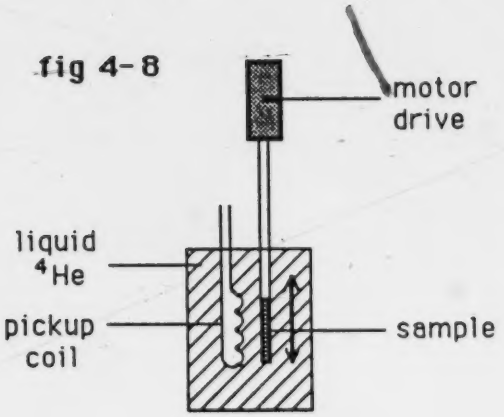
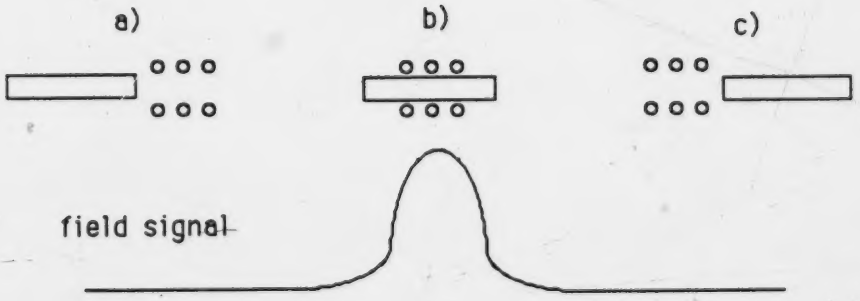



fig 4-9



the magnetization of the sample. This magnetization measurement can then, in turn, be used to find the susceptibility $\chi$ of the sample.

Since the magnetization of a substance is a function of both temperature T and the applied field, H, with the use of the magnetometer, two types of magnetization measurements are possible. One method is to hold the temperature constant and measure the sample's magnetization with respect to changing magnetic field,

(4-15) $M = M(H)\big|_{T=const}$,

while the other is to measure magnetization with respect to changing temperature in a fixed external field,

(4-16) $M = M(T)\big|_{H=const}$.

Measurements for (4-15) can be done with the assistance of a motor drive system to move the sample in and out of the specimen coil (fig 4-8). Given a fixed applied field and the sample outside the coil, the magnetometer will only register the field contribution from the external magnetic field. (fig 4-9a) As the sample is introduced into the coil, the magnetometer will register the change in the field signal due to the introduction of the sample's magnetization. (fig 4-9b) Finally as the sample is removed from the coil, the signal will once again revert to its original value. Since this signal change is caused only by the magnetization of the sample and is independent of the external field, (except for the dependence of $M_s$ on H) the external field can essentially

be "zeroed" (the output reading is set to zero when the specimen is out of the coil) and the amplitude of the signal change can be assumed proportional to the sample's magnetization. For this method, care must be taken that the vibrations caused by the motor drive system are kept to a minimum. If any significant signals due to vibration exist, these will appear as small oscillations or noise on the field change curve. When vibration is minimized one should observe smooth, symmetric curves resulting in accurate magnetization measurements.

When performing magnetization measurements with respect to changing temperature in a constant field, no motion is required and all changes in the magnetometer signal can be assumed to arise from changes in the magnetization of the sample. However, unless one has independent information about the magnetization of the specimen at some temperature within the measurement range, the temperature dependence measurements alone give only the change in the magnetization and not absolute values.

Since the constant applied field may be several kilogauss and we wish to measure magnetization changes of a few milligauss, it is essential to reduce magnetic noise near the specimen coil to about one part in $10^6$ of the applied field.

## 5. Flux-Gate Magnetometer

The magnetometer was built to fit within a 0.5" diameter tube, which is the same size as the tubing which houses the SQUID system in the dilution refrigerator. This was done so that, if the need arise, it could be easily interchanged with the SQUID probe. The field sensor was fitted snugly within the probe coil of the flux transformer and a counter-field coil was wound around the two coils to counteract any unwanted frozen-in fields and "zero" the magnetometer. This coil system fitted within a teflon brace which slid into the lower end of the 0.5" tube. Windows were cut in the tube just above and below the brace and a small circuit board was inserted in the upper window in order to give easy access to the coil connections. A brass sleeve was fitted over the lower section of the tube to protect the windows at other times. The tube-sleeve combination was coated with Pb-Sn solder which becomes superconducting at ~7 K and shields the volume within from external magnetic fields at lower temperatures. Finally, the lower section was wrapped with lead foil to further shield the system from external magnetic fields.

Once made, this field sensor was tested to observe its effectiveness. Initially it was known from the HP 3529A manual that the field sensor was made so that the milliammeter would register 1 mA for every milligauss detected by the field sensor. However it was also known from Andres and Wernick (1973) that the signal efficiency of the

probe drops significantly at helium temperatures. To measure this, a simple dc solenoid was wound around the probe (fig 5-1). This solenoid-probe system was then inserted into a helium bath (4.1 K) and the measurements taken in the bath were compared to those taken at room temperature. Since from equation (4-6), the field produced by a solenoid is proportional to the current in it, the percent change in the sensitivity of the probe due to the temperature change can be measured by observing the percent change required in the solenoid current to maintain the same milliammeter reading. For example, if there is a 20% drop in the sensitivity of the probe due to the temperature change, then 1 m Gauss, which produces 100 mA at room temperature, will only produce 80 mA at 4.1 K. To register the same signal in the milliammeter at both temperatures, the current in the coil would have to be increased by 25% at 4.1 K. The results tabulated in table 5-1 were obtained using the apparatus set up as in fig 5-1 where $r = 1.0\Omega$. From table 5-1, it can be seen that at helium temperatures, the sensitivity of the field sensor is only 78% of its sensitivity at room temperature.

With the field sensor section built and tested, the next step was to construct the flux transformer. This consisted of the probe coil which was already wound around the field sensor and the specimen coil system which was yet to be made. The flux transformer must be superconducting and to increase its versatility it must be made of wire with a high critical temperature and field. 0.006" diameter Nb-Ti

fig 5-1

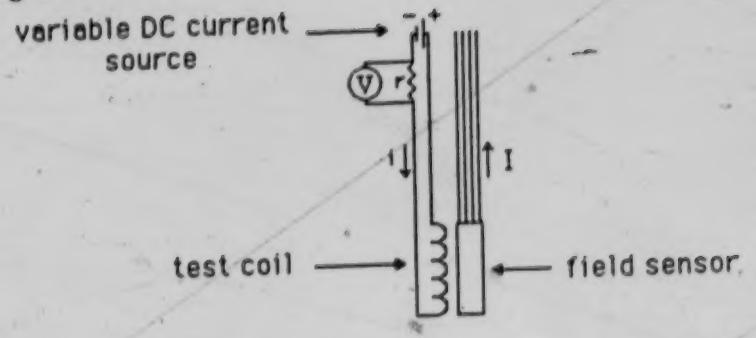
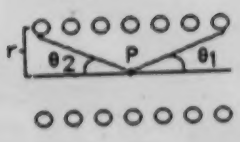

variable DC current source
V
r
I
I
test coil
field sensor

fig 5-2


r
θ2
P
θ1

alloy wire with a critical field of 12 Tesla was selected. All junctions in the flux transformer were spotwelded. This method was chosen over others because of the high critical currents such junctions can withstand (Hall, 1986) and the small space they require. The joints were coated with an epoxy cement for insulation and a heater was wound around a section of the transformer just below the probe coil. It was possible with this heater to break the transformer persistent current if necessary without warming the whole probe.

The specimen coil is wound around a coil form made of fibreglass and is divided into two identical but counter-wound coils. With such an arrangement, a sample that is moved from the centre of one coil to the other will produce two signal peaks of identical size but of opposite direction (fig 5-2). This way, one can measure the magnetization of the sample from the peak to peak value (divided by two) and eliminate the difficulty of trying to locate the zero point. Finally, to avoid mutual inductance from the two coils, there should be a reasonable distance separating them.

Flux transformers for SQUID magnetometers utilize maximum sensitivity by matching the self inductance of the specimen coil with that of the probe coil (Claasen, 1975). Since the flux transformer used here is designed for a particular probe, it too must fulfill the same requirement to achieve maximum output.

TABLE 5-1

| Temperature | i(mA) | I(A) |
|---|---|---|
| 4 K | 0.076 | 0 |
| | 31.424 | 3 |
| 300 K | 19.59 | 0 |
| | 59.66 | 3 |

The inductance of the probe coil was estimated and an astatic specimen coil was constructed. The test involved calculating the transformer ratio of the flux transformer and comparing it with the measured transformer ratio. To do this, a test coil was wound around one of the counterwound specimen coils. The field applied by this coil to the specimen coil was calculated by the equation

$$(5\text{-}1) \quad H = -\frac{nI}{2}\int_{\theta_1}^{\theta_2} \sin\theta d\theta$$

$$= nI/2(\cos\theta 2 - \cos\theta_1)$$

and choosing P as the midpoint along the axial length of the coil. From figure 5-2, when P is at the midpoint of the coil axis, equation 5-1 becomes;

$$(5\text{-}2) \quad H = nI\cos\theta_2$$

where

(5-3) $\cos\theta_2 = (\ell/2)/[(\ell/2)^2 + (r)^2]^{1/2}$

and $\ell$ and r are the length and radius of the coil.

The corresponding field detected by the probe coil could be found by the relation obtained from the field sensor tests,

(5-4) $H(mG) = (0.78)I(ma)$,

at 4.1 K. The entire unit was placed in a liquid $^4He$ bath and the measured transformer ratio was obtained by comparing the field of the test coil with the field registered by the 428 B milliammeter. The relative field data are given in table 5-2 and graph 5-1. From graph 5-1, the field relation turned out to be linear with a slope (whose value gives the transformer ratio) of 0.391. This ratio between the test coil field and sensor field should be comparable to the transformer ratio between the specimen coil and the probe coil. This transformer ratio can be calculated by using equation 5-2 to find the field for both the specimen and probe coils for a given current.

From the coil dimensions given on figure 5-3 and using equation (5-2) and (5-3) the transformer ratio of the probe coil and the half-specimen coil is found to be 0.406. From the comparison of the two ratios, it is evident that the two values are quite close (% discrepancy = 8.6).

With the transformer ratios exhibiting favorable results, the whole magnetometer-refrigerator system could now be assembled. Unfortunately, the lack of time and my

Table 5-2

| Test Coil Field (A/m) | Sensor Field (A/m) |
|---|---|
| 2.72 | 1.02 |
| 5.32 | 2.03 |
| 7.92 | 3.05 |
| 10.44 | 4.07 |
| 13.79 | 5.09 |
| 15.71 | 6.10 |
| 18.40 | 7.12 |
| 21.00 | 8.14 |
| 23.54 | 9.16 |

**GRAPH 5-1**

MEASURED TRANSFORMER RATIO

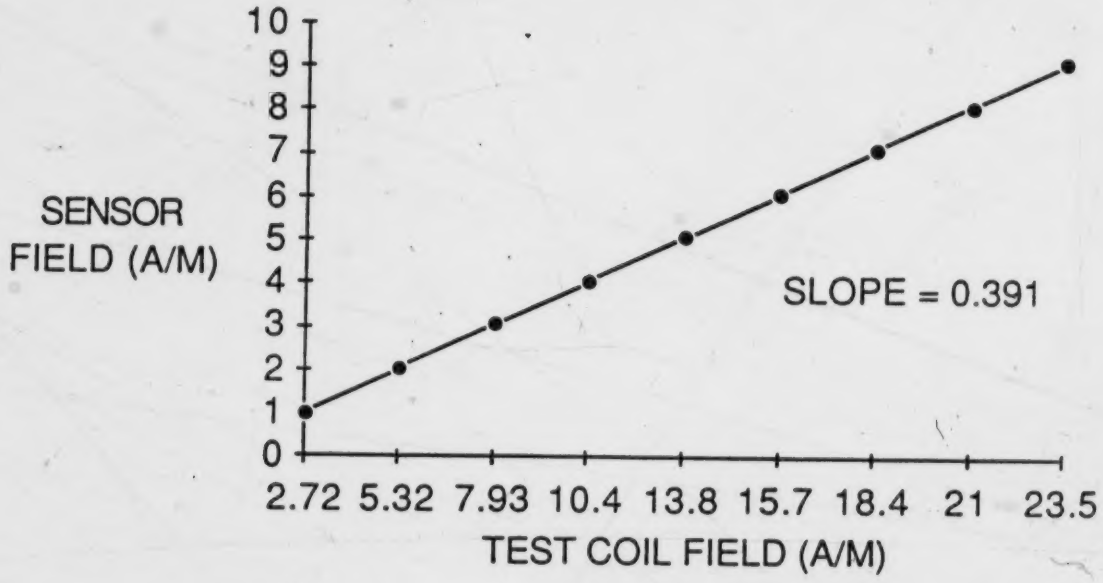
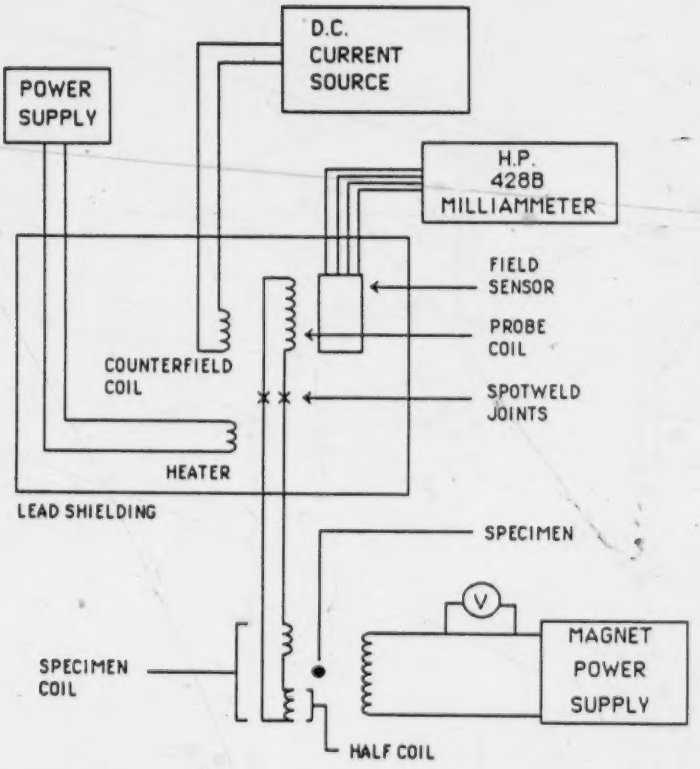


fig 5-3



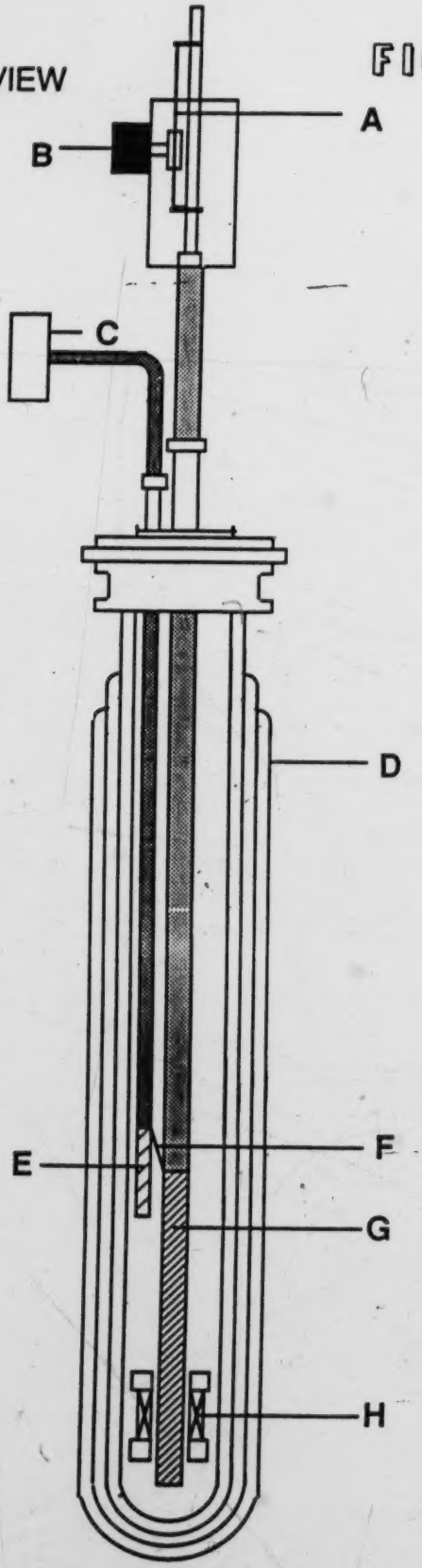

COIL DIMENSIONS:

| | SPECIMEN COIL | PROBE COIL |
|---|---|---|
| LENGTH | | |
| HALF COIL | 0.5 cm. | |
| WHOLE COIL | 2.5 cm. | 2.4 cm. |
| RADII | 0.6 cm. | 0.3 cm. |
| TURNS/UNIT LENGTH | 61.7 turns/cm | 60.9 turns/cm. |

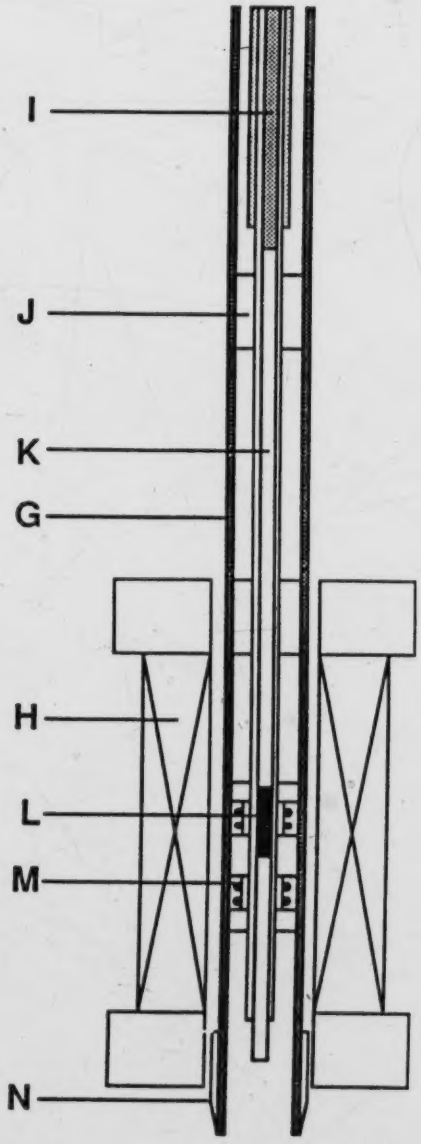
experience in cryogenics and the inoperability of the $^3$He refrigerator at that time made it necessary to use a small $^4$He refrigerating system for our magnetometer. The refrigerator had been designed such that the manometer was connected outside the pumping valve controlling the $^4$He vapor pressure. This limited our experiment to only two temperature settings of 4.1 K (ambient pressure) and 1.4 K (fully pumped). However for those settings the field dependence of magnetization could be observed. The distance of the field sensor from the magnet had to be carefully selected so that it was large enough to keep the lead shields around the sensor from saturating magnetically without making the helium necessary to contain the transformer circuit unnecessarily large. At a distance of 25 cm the magnet could be ramped to about 1.5 T before saturating the lead shields and so this distance was chosen for our experimental set up.

UNIT
OVERVIEW

# Flux Gate Cryostat




SIGNAL PICKUP
SECTION



# Flux Gate Cryostat

A Belt drive system

B Driving motor

C Input/Output box

D $^4$He refrigerator

E Field sensor system

F Flux-gate transformer coil

G Fiberglass tubing

H Superconducting magnet

I Stainless rod

J Fiberglass brace

K Teflon tubing

L Sample

M Flux-gate pickup coil

N Teflon brace

## 6. Experiment

With the apparatus set up and tested, an actual magnetization experiment could be done on heavy fermion $UPt_3$. Polycrystalline $UPt_3$ samples were prepared in an argon filled arc furnace using measured amounts of depleted uranium ($^{235}U$ reduced) and high grade platinum metal. The uranium was 3-9s purity while the platinum was 5-9s grade. The ingot was vacuum annealed at 980°C for 50 hours and X-ray diffraction analysis was done to identify its structure. The Bragg pattern revealed a $MgCd_3$ type D019 structure (Kadowaki et al. 1986) with no extra lines detected. (graph 6-1)

A rectangular piece was cut from the ingot and electrical resistivity measurements were made. (graph 6-2). The sample was found to go superconducting at $T_c = 0.475$ K with $\Delta T_c = 4.2$ mK while the resistance ratio turned out to be $r \equiv R(300\ K)/R(T_c^+) \sim 85$. At temperatures just above $T_c$, the resistivity showed a temperature dependence of

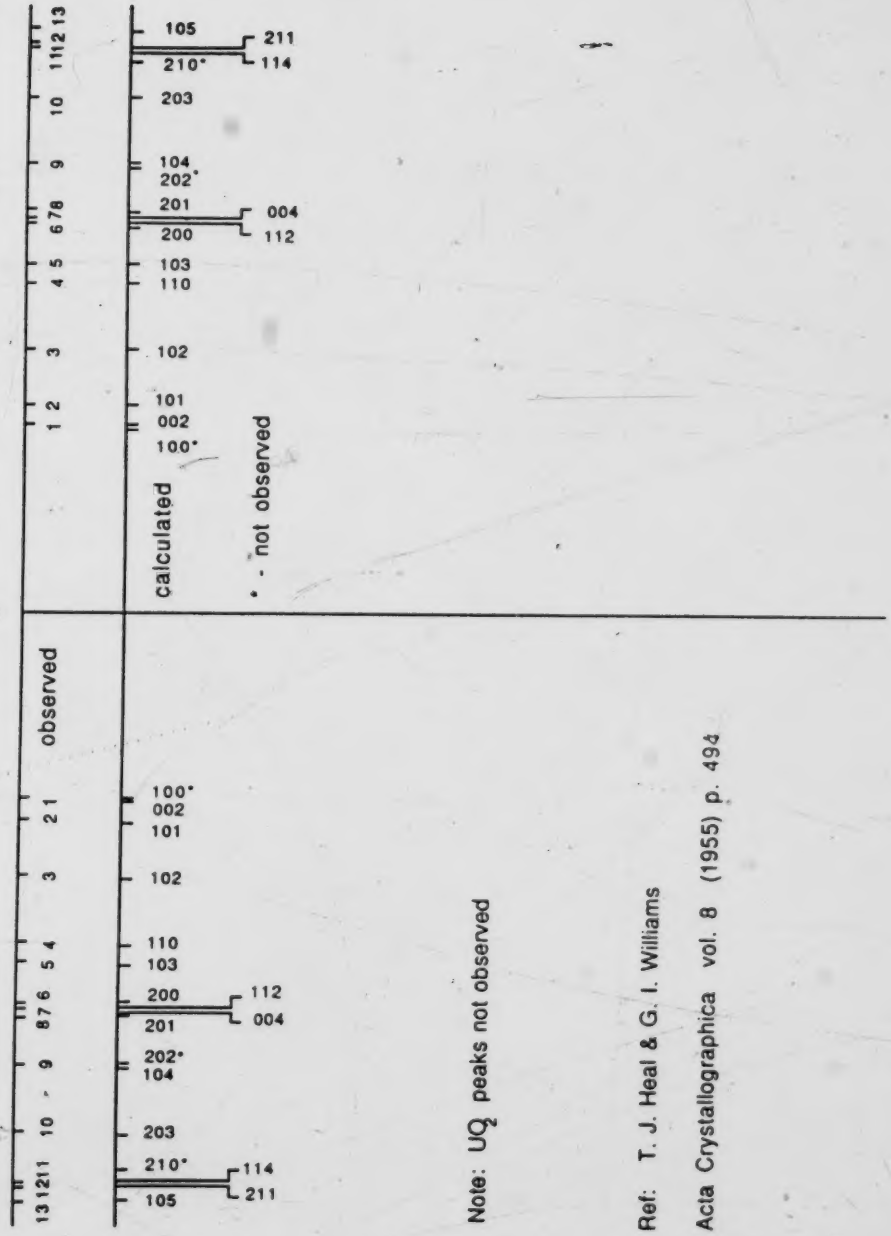
(6-1) $\rho(T) = \rho_o + AT^n$

where $\rho_o = 2.2\ \mu\Omega$ cm, n=1.96 and $A = 2.02\ \mu\ \Omega\ cmK^{-1.96}$. Longitudinal magnetoresistance was also measured and below 4.2 K was found to be positive up to 30 KOe. The field dependence of the magnetoresistance followed the equation;

(6.2) $\Delta\rho(H)/\rho(0) = \alpha H^n$

with n = 1.63 and $\alpha = 3.44\times10^{-4}(KOe)^{-1.63}$ at 0.55 K. This positive magnetoresistance has also been observed by

graph 6-1

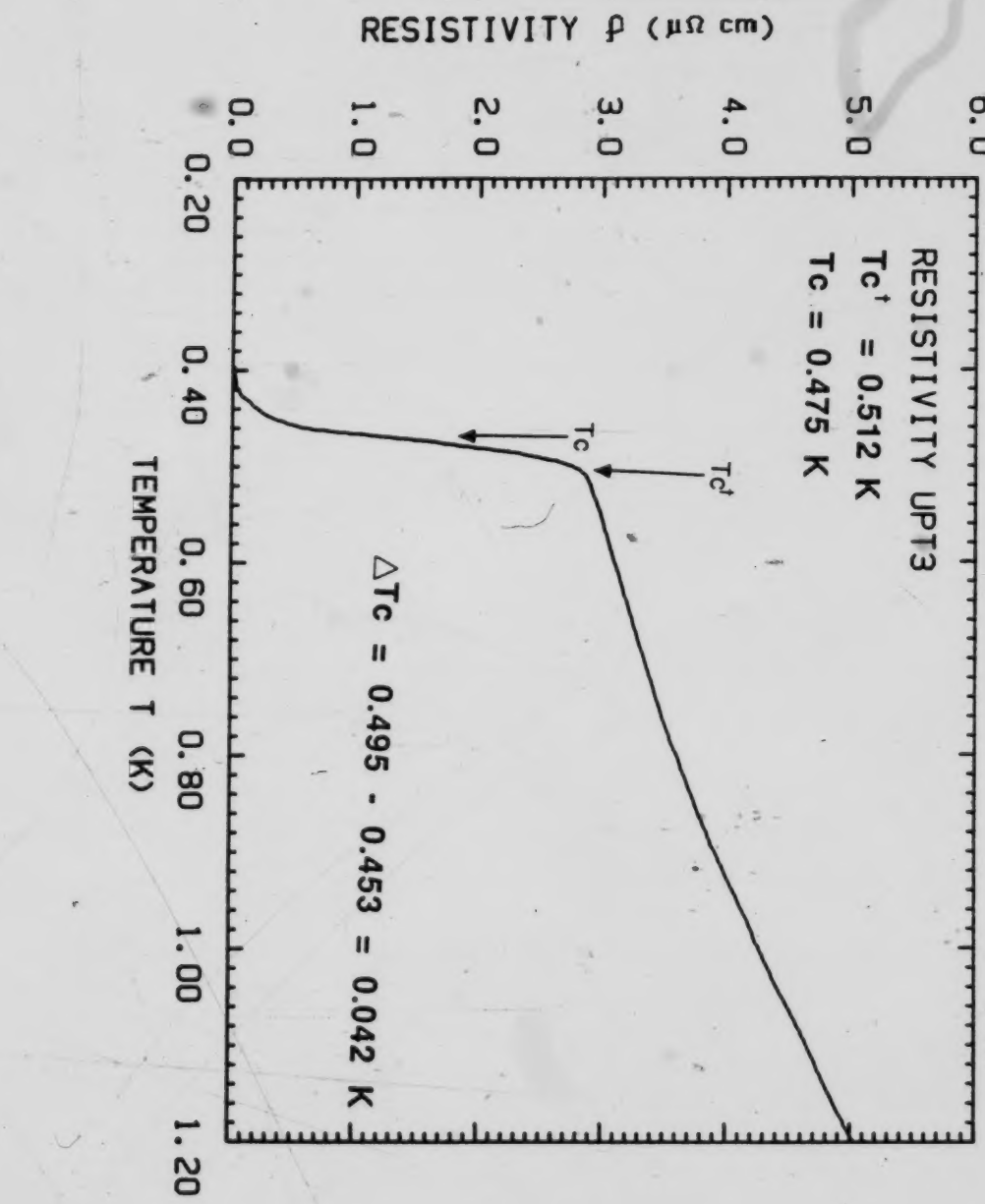



Note: $UO_2$ peaks not observed

Ref: T. J. Heal & G. I. Williams

Acta Crystallographica vol. 8 (1955) p. 494

graph 6-2


RESISTIVITY ρ (μΩ cm)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.20
0.40
0.60
0.80
1.00
1.20
TEMPERATURE T (K)
RESISTIVITY UPT3
Tc' = 0.512 K
Tc = 0.475 K
Tc'
Tc
ΔTc = 0.495 - 0.453 = 0.042 K

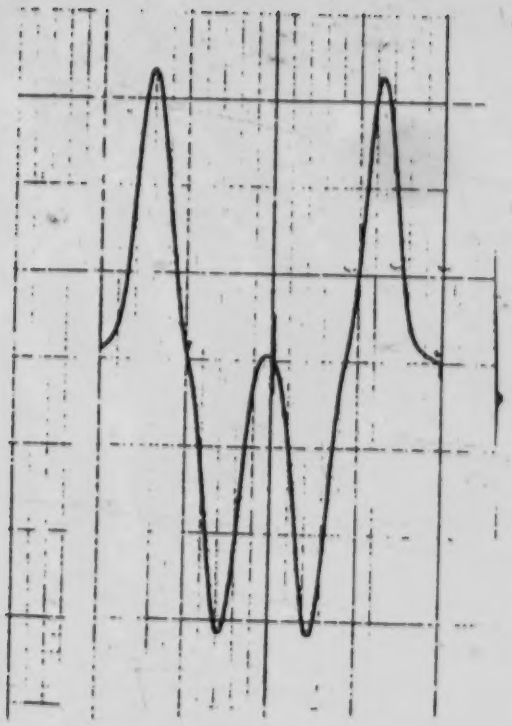
de Visser, Gersdorf, Franse, and Menovsky (1986). Furthermore they observed a large maximum value at 21 T with the applied field along the basal plane. This positive magnetoresistance which is in contrast with other heavy fermion systems may arise from antiferromagnetic spin fluctuations which enhance magnetoresistance as the external field is increased. Yet at zero field no long range magnetic ordering is observed.

The rectangular $UPt_3$ sample was placed within the teflon sample holder of the magnetometer's motor drive apparatus. The sample's 10.0 mm length was ideal for it completely filled the length of a single counterwound specimen coil, yet was short enough to ensure that it never occupied both coils simultaneously. The motor drive system consists of a stainless steel rod which connects to a fiberglass tube of equal diameter. A copper tube is held within the fiberglass tube by two fiberglass braces. The teflon sample holder is inserted within this copper tube. A belt driven steel rod moves the sample holder in and out of the coils. Since the rate of sample movement is not a crucial factor, a belt drive system, which is easier to build and is quieter than a gear drive system, was used. The teflon and fiberglass braces were used in the driving mechanism to maintain vibrational noise at a minimum. Furthermore, a magnet of high homogeneity was used to reduce variations in the external magnetic field. Finally a plotter

was connected to the milliammeter in order to actually observe the shape of the peak as well as increase the accuracy of measurement.

Initial runs were made with the $UPt_3$ sample to observe the signal characteristics. The signals observed were basically free of vibrational noise and their symmetry showed the structural similarity between the two specimen coils. (fig 6-1) Field dependent magnetization measurements up to 17 KOe were done on the $UPt_3$ sample at two temperature settings of 1.4 K and 4.1 K using a glass $^4He$ dewar. At 4.1 K, the sample was immersed in a liquid $^4He$ bath and 20 measurements up to ~17 KOe were recorded. Using a variable current source for the counter-field coil around the sensor, the output was set to zero before the sample was introduced for each measurement. Also the sample was passed through the coil in both directions to obtain two sets of measurements for each field setting. Finally, whenever the external field became too high for the counter-field coil to cancel, a small current was passed through the flux-gate transformer heater to break the persistent current and reset the system. The magnetization-field relationship was observed to be linear with no significant hysteresis effect. For the measurements at 1.4 K, problems appeared when doing the experiment. Because of the small volume of the glass dewar the pumped helium level would fall below the flux-gate transformer before reaching the desired temperature, rendering the

fig 6-1



magnetometer useless. The simplest solution which required no rebuilding of the cryostat was to fill the helium level to the maximum possible and keep the pumping rate to a minimum. This method provided a few minutes in which to do the experiment before the helium level sank below the transformer coils. With only a short time available, only 10 values were obtained for this temperature setting. The magnetization-field relation also turned out to be linear for this temperature, but with a slightly lower slope.

The values obtained from the milliammeter are in dimensions of current; calibration must be done to obtain the field to current ratio between the sample and the milliammeter. Initially, a 3-9 grade test sample of Ni was used. However since nickel is ferromagnetic, its magnetization was observed to be too strong for the high sensitivity of the flux-gate magnetometer. With no other test samples available at the time, the alternative was to wind a calibration coil to put in place of a sample. The coil was wound from #38 gauge Cu wire to approximately the same length as the $UPt_3$ sample. After slight revision of the cryostat to accommodate the current leads to the calibration coil, measurements were once again done at both 4.1 K and 1.4 K. The field within the coil was found from its current using equation (5-1). The calibration data have been tabulated on tables 6-1 and 6-2 for temperatures 4.1 K and 1.4 K respectively and plotted on graphs 6-3 and 6-4. From

the graphs it can be seen that there is very little difference between the two temperatures with both measurements resulting in a field/current ratio of 15.2 mG/mA. Thus a single field to current ratio can be used for the calibration at both temperatures.

Now the milliammeter current, I is proportional to the total flux change in the specimen coil, $\Delta\phi_c$, thus we may write

(6-3) $I = k\Delta\phi_c$

(6-4) and $k^{-1} = 15.2 \frac{mG}{mA} A_c$

where $A_c$ is the cross-sectional area of the test coil. If instead, the flux change in the specimen coil is produced by introducing a specimen of cross-section $A_s$ and magnetization $M_s$ then

(6-6) $B_s = 4\pi M_s$

assuming the effect of H has been cancelled by zeroing the magnetometer after H is applied and before the specimen is introduced. Also

(6-7) $\Delta\phi_s = B_s A_s$.

Combining these equations the relationship between the specimen magnetization and the milliammeter current is

(6-8) $M_s = \frac{15.2}{4\pi} \frac{A_c}{A_s} I \frac{mG}{mA}$

For the test coil and $UPt_3$ specimen

$$A_c/A_s = 2.47$$

and then

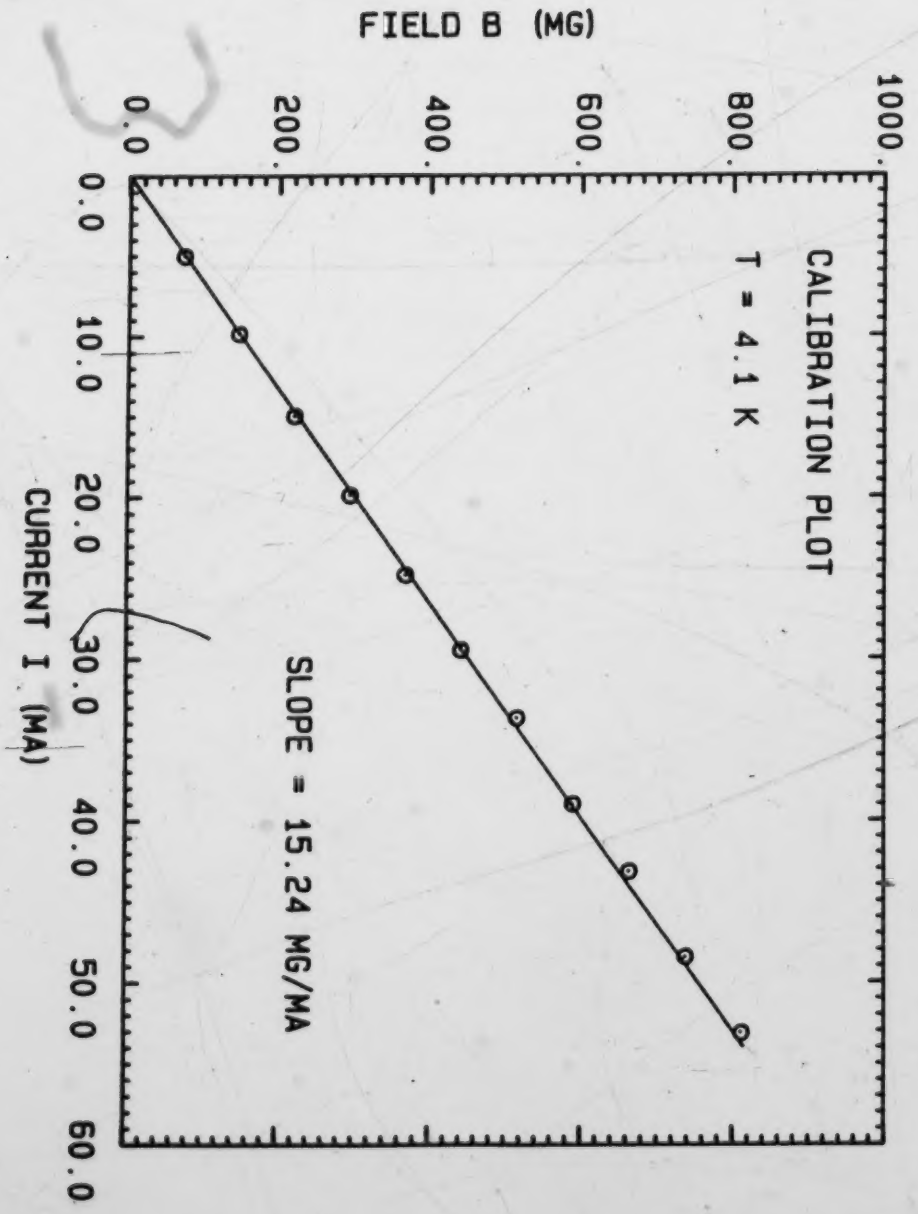
Table 6-1

| H.P. Milliammeter Reading I (mA) | Test coil field B (mG) |
|---|---|
| 1.0 | 73.81 |
| 2.0 | 147.61 |
| 3.0 | 221.42 |
| 4.0 | 295.23 |
| 5.0 | 369.04 |
| 6.0 | 442.84 |
| 7.0 | 516.65 |
| 8.0 | 590.46 |
| 9.0 | 664.27 |
| 10.0 | 738.07 |
| 11.0 | 811.88 |

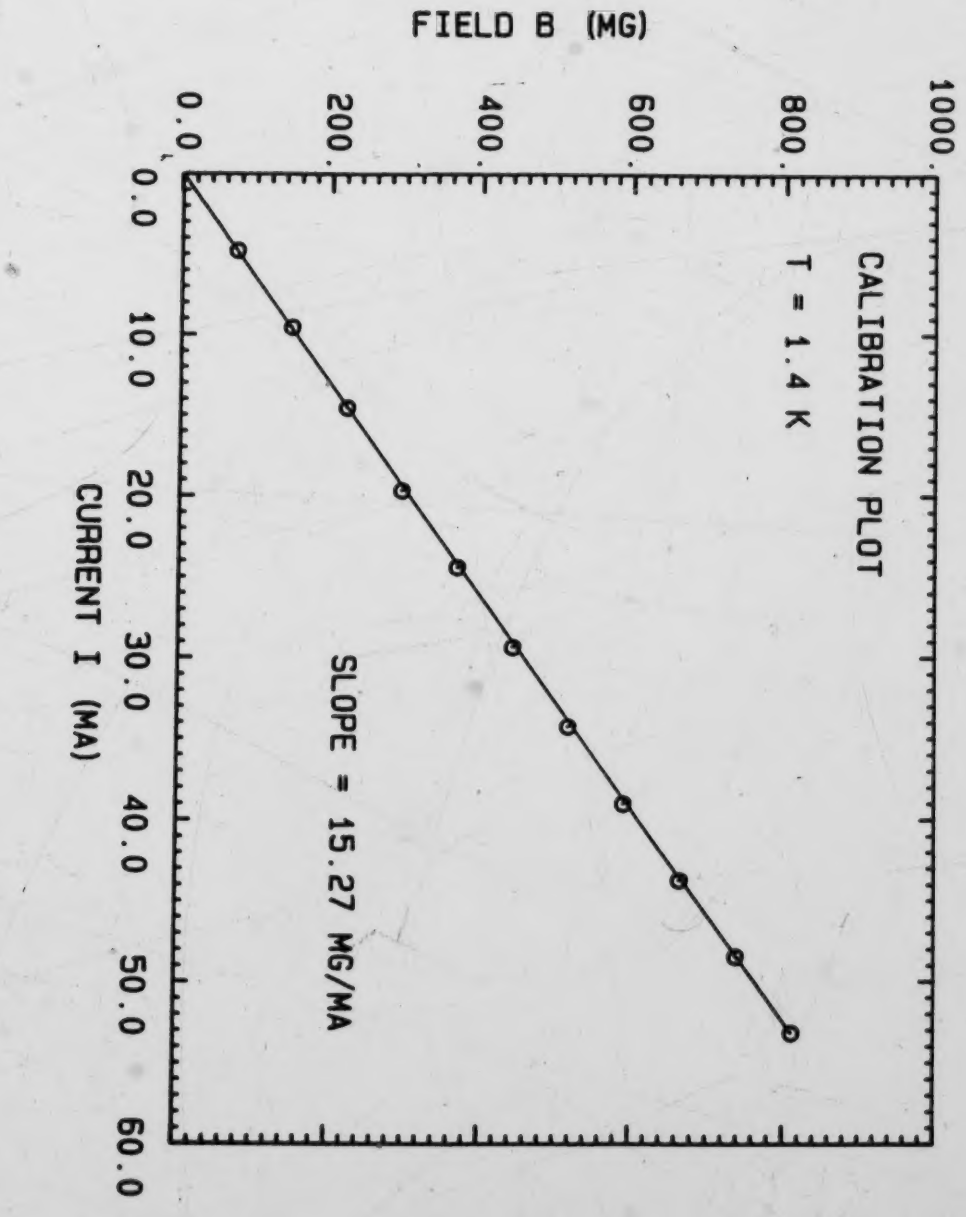
Table 6-2

| H.P. Milliammeter Reading I (mA) | Test coil field B (mG) |
|---|---|
| 1.0 | 73.80 |
| 2.0 | 147.61 |
| 3.0 | 221.41 |
| 4.0 | 295.21 |
| 5.0 | 369.01 |
| 6.0 | 442.81 |
| 7.0 | 516.62 |
| 8.0 | 590.42 |
| 9.0 | 664.22 |
| 10.0 | 738.02 |
| 11.0 | 811.83 |

graph 6-3


FIELD B (MG)
0.0
200.
400.
600.
800.
1000.
CALIBRATION PLOT
T = 4.1 K
SLOPE = 15.24 MG/MA
0.0
10.0
20.0
30.0
40.0
50.0
60.0
CURRENT I (MA)

graph 6-4


FIELD B (MG)
0.0
200.
400.
600.
800.
1000.
CALIBRATION PLOT
T = 1.4 K
SLOPE = 15.27 MG/MA
0.0
10.0
20.0
30.0
40.0
50.0
60.0
CURRENT I (MA)

(6.9) $M_s = (37.5/4\pi)I \cong 2.98\ I\ mG/mG$

Using this equation for calibration, the current signal registered by the H.P. 428B can now be coverted to the corresponding values of magnetization. These values have been tabulated on tables 6-3 and 6-4 for the temperatures of 4.1 K and 1.4 K respectively and plotted on graphs 6-5 and 6-6. From these magnetization measurements, susceptibility values could now be obtained for both temperature settings. To do so recall that

(2-18) $M = \chi H$.

Therefore, the slope of the M-H curve should give the value of the magnetic susceptibility of $UPt_3$ at each temperature. Since susceptibility values are often measured in terms of emu/mol, it is appropriate to rewrite the magnetization measurements in terms of these units. The electromagnetic unit of magnetization is equivalent to Oerstead $cm^3$, and so to change the values of magnetization

(6-10) $M'(emu/mol) = M(Oe)m/\rho$

where m is the molar mass and $\rho$ is the density of the material.

From the values of $\rho$ and m given in Ch. 3 for $UPt_3$, the values of magnetization rewritten in dimensions of emu/mol becomes

(6-11) $M' = 42.4\ M$ emu/mol

Now

Table 6-3

Temperature = 4.1 K

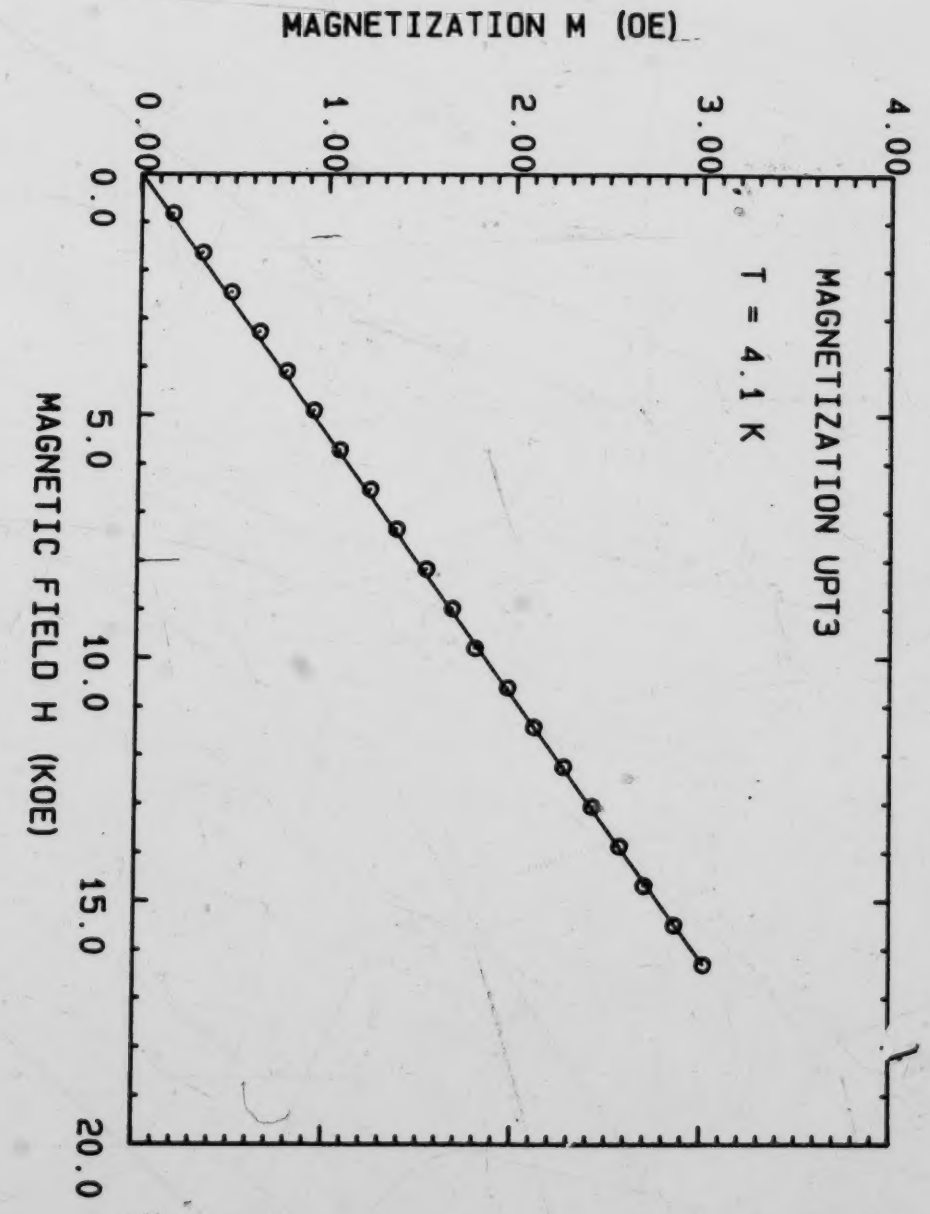
| Applied Field H (KOe) | Magnetization M(Oe) |
|---|---|
| 0.82 | 0.17 |
| 1.63 | 0.33 |
| 2.45 | 0.48 |
| 3.26 | 0.64 |
| 4.08 | 0.78 |
| 4.89 | 0.93 |
| 5.71 | 1.07 |
| 6.52 | 1.23 |
| 7.33 | 1.37 |
| 8.15 | 1.53 |
| 8.96 | 1.67 |
| 9.78 | 1.80 |
| 10.50 | 1.97 |
| 11.41 | 2.11 |
| 12.23 | 2.27 |
| 13.04 | 2.42 |
| 13.86 | 2.57 |
| 14.67 | 2.70 |
| 15.48 | 2.86 |
| 16.30 | 3.02 |

Table 6-4

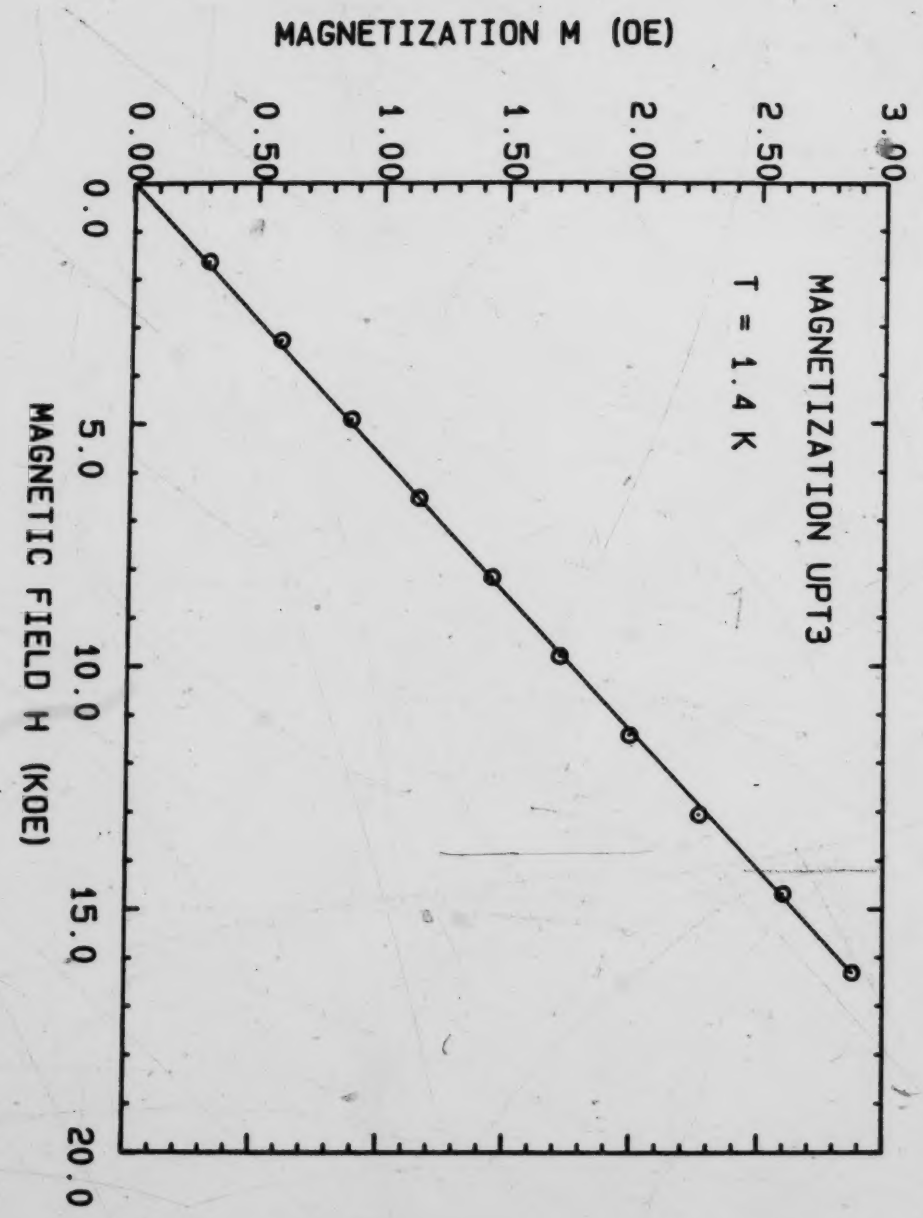
Temperature = 1.4 K

| Applied Field H (KOe) | Magnetization M(Oe) |
|---|---|
| 1.63 | 0.30 |
| 3.26 | 0.50 |
| 4.89 | 0.88 |
| 6.52 | 1.15 |
| 8.15 | 1.45 |
| 9.78 | 1.72 |
| 11.41 | 1.99 |
| 13.04 | 2.27 |
| 14.67 | 2.60 |
| 16.30 | 2.88 |

graph 6-5


MAGNETIZATION M (OE)
0.00
1.00
2.00
3.00
4.00
MAGNETIZATION UPT3
T = 4.1 K
0.0
5.0
10.0
15.0
20.0
MAGNETIC FIELD H (KOE)

graph 6-6


MAGNETIZATION M (OE)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
MAGNETIZATION UPT3
T = 1.4 K
0.0
5.0
10.0
15.0
20.0
MAGNETIC FIELD H (KOE)

(6-12) $\chi = M'/H = 42.4(M/H)$ emu/mol

Using (6-12), the slopes of the magnetization curves for the temperatures of 4.1 K and 1.4 K become $7.9\times10^{-3}$ emu/mol and $7.5\times10^{-3}$ emu/mol respectively. these values correlate quite well with the $\chi(t=0)$ value of $8.2\times10^{-3}$ emu/mol observed by Frings et al. (1983) for their polycrystalline sample of $UPt_3$. For normal metallic systems, the magnetic susceptibility is of the order of $\sim10^{-5}$ emu/mol. Assuming much of the susceptibility is due to paramagnetic behavior of the electrons, this large $\chi$ agrees with other measurements, that is, the effective mass of the charge carriers is very large in $UPt_3$.

The decrease in $\chi$ as the temperature decreased from 4.1 K to 1.4 K also agrees with measurements by Frings et al. on both polycrystalline and single crystalline $UPt_3$ samples. They saw a net rise in susceptibility with decrease in temperature until at about 25 K , it attained a maximum and began to decrease. This behavior is characteristic of antiferromagnetic systems and would comply with the antiferromagnetic spin fluctuation behavior observed in the magnetoresistance. Yet the absence of any observed magnetic ordering in zero field is then quite amomalous. It has been speculated that this system may be of helical spin structure.

## 7. Conclusion

The flux gate magnetometer was successfully built and tested. With the flux gate magnetometer, the magnetization behavior of $UPt_3$ up to 1.6 T has been observed at the two temperatures 4.1 K and 1.4 K and the corresponding susceptibilities found. The magnetization curves were found to be linear in applied field with no meta-magnetic behavior occurring at 1.6 T. The magnetic susceptibility at 4.1 K and 1.4 K were $7.9 \times 10^{-3}$ emu/mol and $7.5 \times 10^{-3}$ emu/mol respectively which are approximately two orders of magnitude greater than that of normal metals. Assuming these large $\chi$ values result mainly from paramagnetism of the electrons, it validates the large effective mass value observed by the specific heat measurements. Furthermore the decrease in $\chi$ as the temperature went from 4.1 K to 1.4 K agreed with that observed by Franse et al. The temperature dependence of $\chi$ seemed characteristic of antiferromagnetic systems which would agree with the antiferromagnetic spin fluctuation characteristic observed in the magnetoresistance.

With the success of this experiment, it is now possible to look into future experiments. With $UPt_3$ going superconducting at ~0.5 K it would be of great interest to observe its magnetization characteristics below the critical temperature. This requires the remounting of the flux-gate system within a dilution or a $^3He$ refrigeration system and the building and testing of a new flux-gate transformer

system for that refrigerator.

With the present refrigeration system, a rebuilding of the gas handling system is necessary to make temperature dependent measurements of magnetization possible. Also the system would benefit from any revisions done to increase its efficiency. Finally, the lead shielding used to keep external magnetic noise away from the field sensor should eventually be replaced by a material with a higher critical field (i.e. Niobium) making magnetization measurement possible for higher external fields.

As far as heavy fermion systems are concerned more information is necessary before we can fully understand their behavior. Such information can be obtained in two ways; by discovering more heavy fermion compounds and by doing more experiments on the compounds already in existence. In any case the path towards this goal is still a long and difficult one. However with the completion of this thesis I feel we are one step closer to reaching a full understanding of heavy fermion systems and their electronic interactions.

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